3. A LASER INITIATED EXPLOSIVE DEVICE SYSTEM*

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SUMMARY

A laser initiated explosive system has been recently developed which can simultaneously initiate multiple explosive devices. Advantages of this system over electrically initiated devices (EED's) are increased safety and reliability, simplicity of laser initiated devices, and increased weight efficiency. The system design with test data is presented and a comparison between laser initiation and electrical initiation is discussed.

INTRODUCTION

There are numerous applications for explosive devices aboard spacecrafts and launch vehicles. In most cases these devices are electrically initiated. The mechanism in hot-bridgewire type electroexplosive devices (EED's) is quite simple. However, the electrical system (power supply, cabling, EED) is a complex work in design, fabrication, and testing because of severe requirements on safety, reliability, and weight efficiency. Inherent disadvantages of EED's are manifold. For example, EED's can be inadvertently initiated from electro-magnetic radiation, spurious electrical signals and/or static discharges. There have been approaches to remedy some of these problems; e.g., initiation sensitivity of EED's has been reduced with the well known 1 watt, 1 amp no-fire squibs using a ceramic header as a heat sink, antistatic gaps and breakdown conductive shunt materials to by-pass static discharges, and electrically nonconductive explosive materials. The bridgewire/header/explosive interface is the most critical area of an EED and has always been the main source of EED unreliability due to poor bridgewire welds, corrosion of the bridgewire, and poor contact between the wire and the explosive. Detailed quality control is necessary to minimize these

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problems, but at very high cost. Nevertheless, there are areas which are so intrinsic that no adequate solution (such as the strain behavior of bridgewire under local heating of the wire or mismatch of its thermal expansion with respect to the bridgewire support) has been found.

A laser initiated explosive device system consists of three parts: A pulsed laser as the power source, fiber optics as the energy transmitter, and laser-initiated explosive devices. The advantages of a laser-initiated device are immediately apparent from Figure 1. It is constructed with the same dimensions as a typical 1 amp, 1 watt no-fire squib, except the electrical connector has been redesigned to accept a fiber-optics bundle. The bridgewire/header subassembly has been replaced with a glass-to-metal sealed window designed to withstand the maximum pressure generated by the explosion. The elimination of the bridgewire and the associated hazards is directly responsible for the elimination of at least 80% of the testing procedures normally required on an EED. These include fabrication of the header, pin to header seal, the spark gap, anti-static shunt, welding of bridgewire, application of explosive slurry to the bridgewire, bridgewire resistance test, pin to case and pin to pin insulation resistance test, electrostatic discharge test, 1 watt, 1 amp no-fire test, post-fire resistance test, temperature cycling test, and various non-destructive tests. To establish these procedures and the quality assurance at each step has been the main effort in the manufacture and qualification of aerospace squibs.

It is realized that laser initiation is energetically more efficient than a 1 watt, 1 amp no-fire hot wire ignition. The laser sensitivity (1 msec laser pulse) of a typical pyrotechnic mixture (Zr/NH_4ClO_4, 50/50) is of the order of 0.93 J/cm^2 (6 J/in.^{2}) while millisecond firing sensitivity of typical 1 watt, 1 amp no-fire squibs are about 6 to 9.3 J/cm^2 (40 to 60 J/in.^{2}) average energy flux at the wire-explosive interface for a typical 1 ohm bridgewire, 2.54mm in length and 0.05mm in diameter (100 mil x 2 mil). The high flux rate required of the latter results from the fact that the header (alumina) which is a good thermal conductor is in contact with the wire and the heat transfer is more efficient. Reliabilitywise, the laser device has more advantages than the electrical hot-wire devices. The mechanism of heat conversion is directly on the explosive in the former case, while the latter has to rely on bridgewire heating and transfer to the explosive. There are possibilities of bridgewire burnout without the resultant explosive ignition. (This is an important mode of failure in a high current, low temperature firing or if an insensitive explosive is used.) When one considers the area of contact of the explosive and the energy it is seen that the laser initiation is less critical to pyrotechnic inhomogeneity. The interface in a laser initiation is typically a 2mm diameter (80 mils) or 32 x 10^{-3} cm^2 (5 x 10^{-3} in.^{2}) in area of initiation, while for a bridgewire 0.05 mm diameter (2 mil) by 2.54 mm long (100 mil) the area is in the order of 20 x 10^{-4} cm^2 (3.2 x 10^{-4} in.^{2}).

It is interesting to note that a laser initiation system can have a weight advantage over an electrical initiation system. At first glance, the laser technique appears to be inefficient in the energy storage. A pulsed solid state laser returns only of the order of 2 to 3% of the electrical energy

needed to excite a flash lamp for laser pumping. However, the specific efficiency of capacitors to store energy increases nonlinearly depending upon the charging voltage. For a typical 50 V tantalum electrolytic capacitor used on a spacecraft for an electrical initiation system the factor is about 11.0 J/Kg (5J/lb) while the aluminum-polyester type (5 kV) and aluminum electrolytic (500 V) energy storage capacitors for laser flash lamp discharge can be as high as 275 J/Kg (125J/lb) and 440 J/Kg (200J/lb), respectively. This fact alone is enough to make the weight efficiencies compatible. On the other hand, the switching and triggering circuitry of a laser initiation system can be made much simpler than an electrical system (especially for simultaneous multi-unit actuation) and be weight saving. This plus the inherently better sensitivity of laser initiation makes it possible for a properly designed laser initiation system to be lighter than an electrical initiation system of the same capability.

LASER SYSTEM DESIGN

Listed below are some of the state-of-the-art considerations in designing a laser initiation system:

1. For pyrotechnic initiation a pulsed neodymium laser operated in the free running mode with a pulse length from 0.2 to 2.0 milliseconds is best suited for laser and pyrotechnic initiation efficiency.

2. Pyrotechnic laser initiation sensitivity is assumed to be 0.93 J/cm^2 (6 J/in.^{2}) which can be achieved, e.g., with a mixture of Zr/NH_4ClO_4 (50/50).

3. The reflective losses of light energy on all optical interfaces such as the focusing lens surface and fiber optic ends, etc., can be reduced to a negligible amount by using anti-reflection coatings.

4. For better transmission of the laser wavelength (1.06 μ), glass fiber optics is preferable to plastic fiber optics. The transmission factor I/I_o is defined as:

$$I/I_o = e^{-\alpha x}$$

   where α is the attenuation constant, with a typical value of 0.4/m for fiber bundle containing 0.075 mm (3 mil) diameter individual glass fibers and x is the length of the fiber optics in meters.

5. For better reliability and ease of fabrication, the fiber bundle of conventional glass fiber optics should have a minimum diameter of 1.65 mm (65 mils).

6. The weight of such types of fiber optics is about 22.4 g/m (0.015 lb/ft) or less, including proper flexible metal cable protection.

7. The relevent quantity of the system is the energy flux density, J/cm^2 ($J/in.^2$); in general, in order to increase the initiation efficiency and to compensate for the rather large loss factor in the fiber optics, the laser beam should be focused to feed into the fiber optics. For a fixed laser beam divergence, the shorter the focal length of the lens, the higher energy flux density at the focal point. However, in practice, focal length of 12.7 to 25.4 mm (0.5 in. to 1.0 in.) is proper in order to match the beam diameter. Too sharp a focus usually will result in burning the input end of the fiber bundle and cause large insertion losses. It will also limit the transmission to only a few individual fibers thereby decreasing the reliability. It is always possible to match the laser spot with the input fiber bundle diameter by adjusting the distance between the lens and the input end of the fiber optics. A detailed study of the flux distribution at the input end is helpful. However, under this condition an average energy flux density Φ can be assumed as:

$$\Phi = \frac{\text{Energy}}{A}$$

where A is the area of the input fiber bundle of diameter 1.65 mm (0.065 in.) for a single fiber bundle, single device application. For multi-devices and a multi-bunched fiber bundle,

$$\Phi = \frac{\text{Energy}}{NA}$$

where N is the number of the devices or fiber bundle branches.

8. With proper design, pulsed neodymium laser may have specific efficiency, i.e., laser energy output per unit weight or volume, of the order of 3.3 J/Kg (1.5 J/lb) and 0.005 J/cm^3 (0.08 $J/in.^3$). (References 1 and 2).

9. With proper design, laser output energy should be about 2% of the electrical energy stored in the high voltage energy storage bank.

10. The required dc input power for the laser can be estimated as

$$\text{Average dc input power} \approx \frac{1}{e} \, \frac{\text{Electrical energy in the capacitor bank}}{\text{Required charging time}}$$

where e is the efficiency factor of a dc to dc high voltage converter. For a properly designed converter, e > 50%.

11. The following is an example illustrating the use of these estimation procedures:

Requirements: Simultaneously initiate four devices over a distance of 3.05 m (10 feet).

Laser sensitivity of device = 0.93 J/cm^2 (6J/in.^{2})

Transmission factor of 3.05 m (10 ft) of fiber optic $\approx$ 20%

Energy flux density required at input end of the fiber optics, X

$$\Phi = 0.93\ J/cm^2 \div 20\% = 4.65\ J/cm^2 = 30\ J/in.^2$$

Laser energy required = NA Φ

$$= 4 \times \pi \times \left(\frac{1.65\ mm}{2}\right)^2 \times 4.65\ J/cm^2$$

$$= 0.4J$$

Laser energy required to satisfy a performance margin of 3

$$= 0.4J \times 3 = 1.2J$$

Weight of laser = 1.2J $\div$ 3.3J/Kg = 364g = 0.8 lb

Size of the laser = 1.2J $\div$ 0.005 J/cm^3 = 240 cm^3 = 15 in.^{3}

Weight of the fiber optics = 4 x 3 m x 22.4 g/m

= 269g = 0.6 lb

It is evident that the procedure is quite simple and effective.

A PRACTICAL EXAMPLE OF THE SYSTEM

A miniaturized laser initiation system has been developed very recently in the Jet Propulsion Laboratory. The objective was to satisfy the requirements stated above. This type of functional requirement is very typical for spacecraft applications, e.g., the Viking Lander separation mechanism. At the beginning of the development it was not quite certain what values of specific efficiency would be achieved since, when the optical pumping level is low, it is known that the lasing threshold condition takes an important role. The optimization of a pulsed neodymium laser is a formidable problem, because the laser efficiency depends essentially on the total efficiency of each link in the chain of laser generation. After careful selection of components and a systematically optimized design and fabrication program, we were able to achieve high energy storage efficiency, good spectral range of the xenon flash lamp, and a laser head configuration for high laser output efficiency. The construction of the laser is shown in Figure 2. It has a dimension of 5.08 x 7.62 x 12.7 cm (2 in. x 3 in. x 5 in.), weighs 774g (1.7 lb) and gives out a laser pulse, 2.8J in energy and 1.5 msec in duration. It requires 10 watts average dc input in a charging time of about 50 sec. The capacitor bank is a 520 V rated, 1200 μf, electrolytic capacitor 5.08 x 11.9 cm (2 in. x 4.68 in.) in size and 340g (12 oz) in weight. The details of the design are reported elsewhere (Reference 2).

Figure 3 shows the test set-up to demonstrate the simultaneous initiation of four explosive devices (the type shown in Figure 1). The fiber optics for this particular type of test was fabricated to have a single input 3. 3 mm in diameter (0. 130 in.) and branched into four identical outputs (1. 65 mm in diameter (0. 065 in.). The total length to each pyrotechnic device was 3. 05 m (10 ft). Randomization of the individual fibers resulted in equal light splitting within ±5% at each output and independent of the light input distribution. The gas pressure generated by the burning pyrotechnic material was monitored by the same method as that used for spacecraft electroexplosive devices. The system consists of 1 cc pressure bomb, Kistler pressure transducers and charge amplifiers. The result of the test as recorded by an oscilloscope is shown in Figure 4. The sharp-rise peak pressure in each channel was reached within approximately 0. 1 ms after the start of the laser pulse. This type of ignition characteristic is very desirable for the functioning of pyrotechnic devices. In comparison with the total laser pulse duration of 1. 5 ms, the laser energy of 2. 8J gives approximately a performance margin of 10. Therefore for a performance margin of three the laser can be further reduced more than 50% to the size and weight estimated in the last section. It is interesting to note that the pyrotechnic switching (firing) unit on the Viking Orbiter '75 spacecraft of the similar capability is 9. 8 x 15. 2 x 23. 4 cm (3. 875 in. x 6. 0 in. x 9. 2 in.) in size and weighs 3. 18 Kg (7. 0 lb).

CONCLUSION AND REMARKS ON THE FUTURE

The novel features of a laser initiated explosive device system, especially in comparison to an electroexplosive initiation system have been demonstrated. It is evident that the system has gone through a speculative stage since the late 60's and has materialized towards a realistic system. Further evaluations should be made with respect to specific needs. There are minor details such as developing a rotary electro-optical or mechanical scanning system of the laser beam or fiber optics for a programmed firing sequence of multi-events, a hermetically sealed fiber optic feed through connector, etc. They can be engineered to be weight efficient and reliable.

The results illustrated here are more or less oriented toward the pyrotechnic system for spacecraft-type application. The concept of laser initiation of explosive devices in general has also been proven to be effective. For example, zirconium doped PETN and RDX can be initiated by the same type of laser, resulting in a burn to detonation. The laser sensitivities are in the order of 3. 1 J/cm^2 (20J/in. ^{2}). Primary high explosives such as lead azide and lead styphnate can be directly initiated. (Reference 3). Q-switched mode lasers can directly detonate PETN, RDX and Tetryl in a properly designed device (References 4 and 5) and can be useful where microsecond simultaneity is important.

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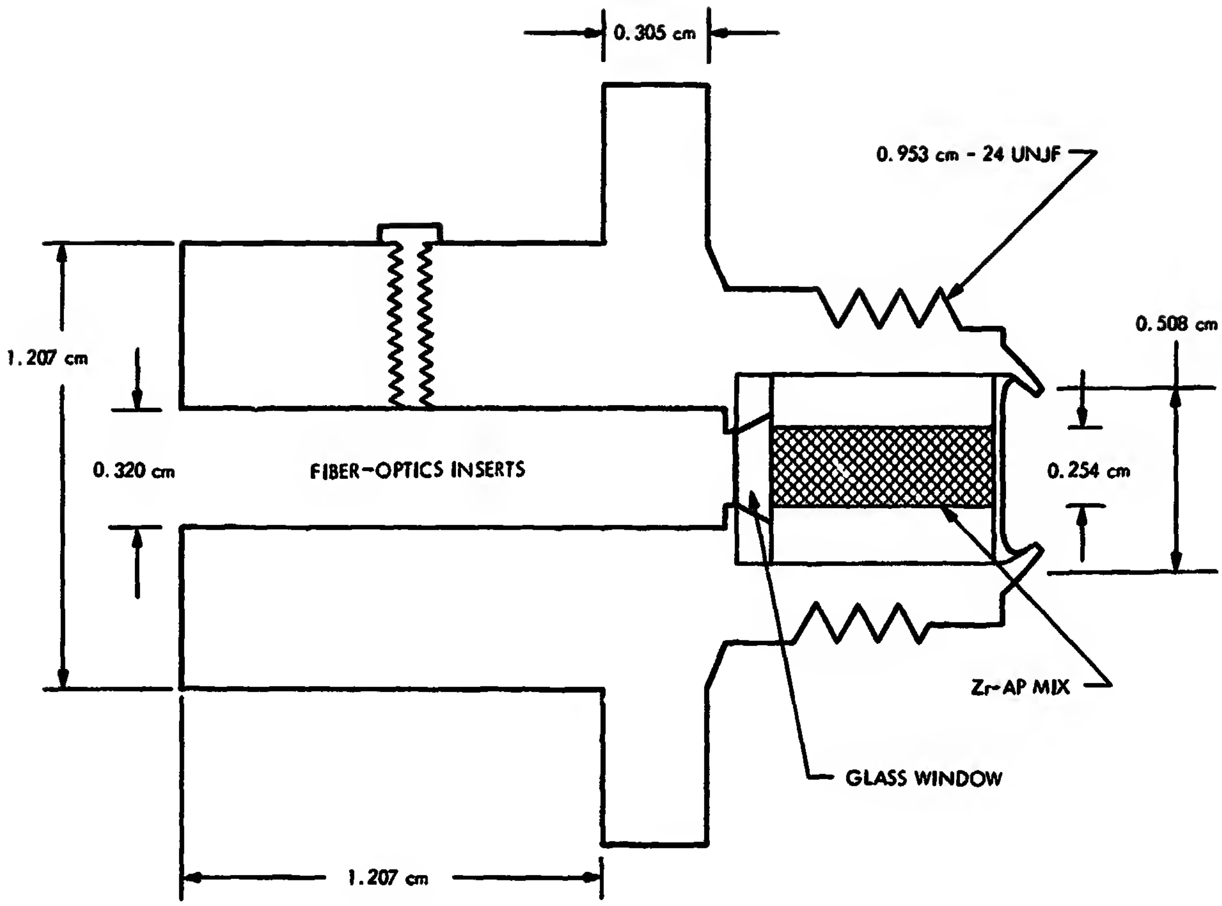


Figure 1.- Laser-initiated pyrotechnic device.

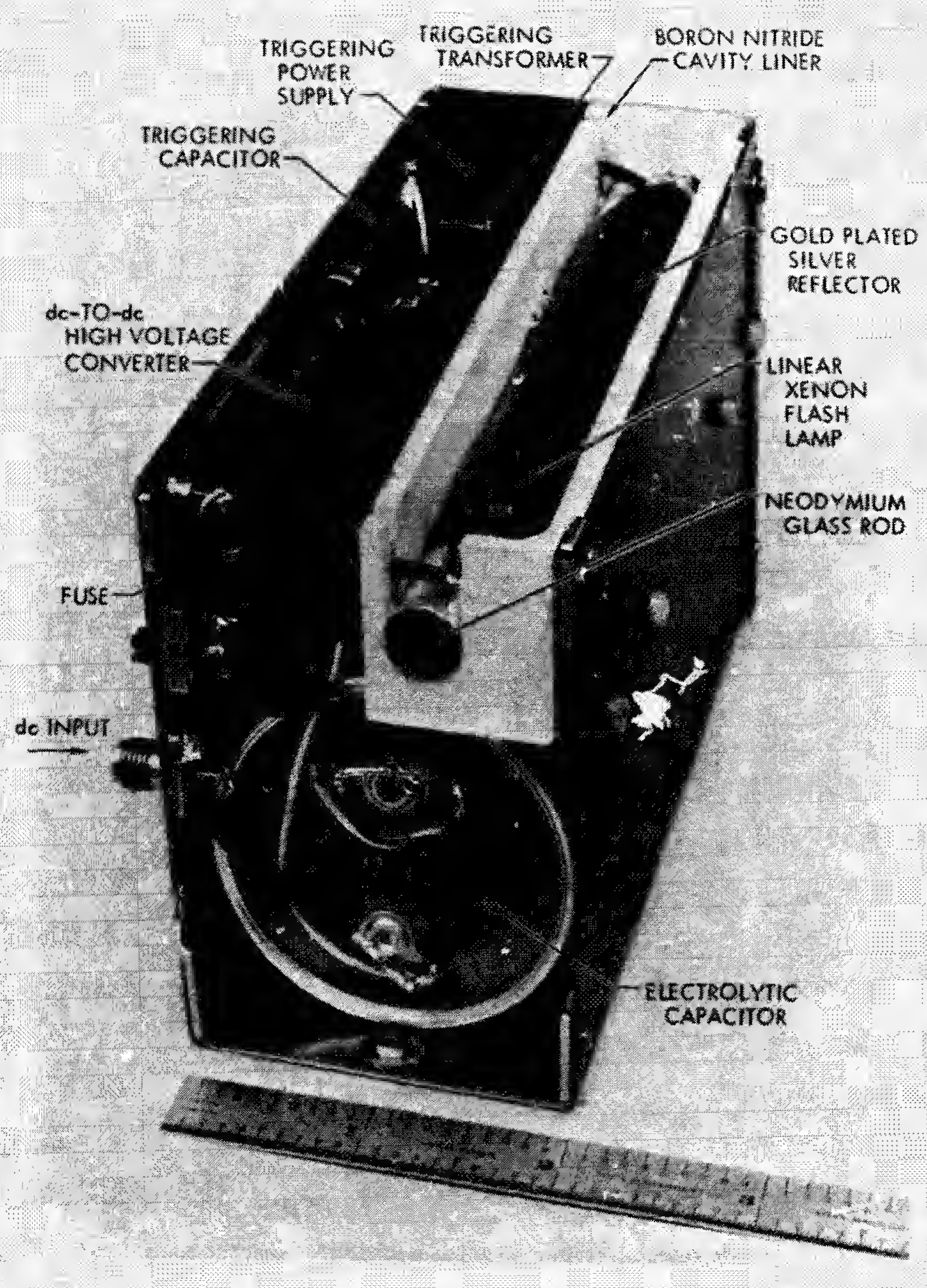


Figure 2.- Interior of a high-efficiency, small, pulsed neodymium laser showing the components and construction.

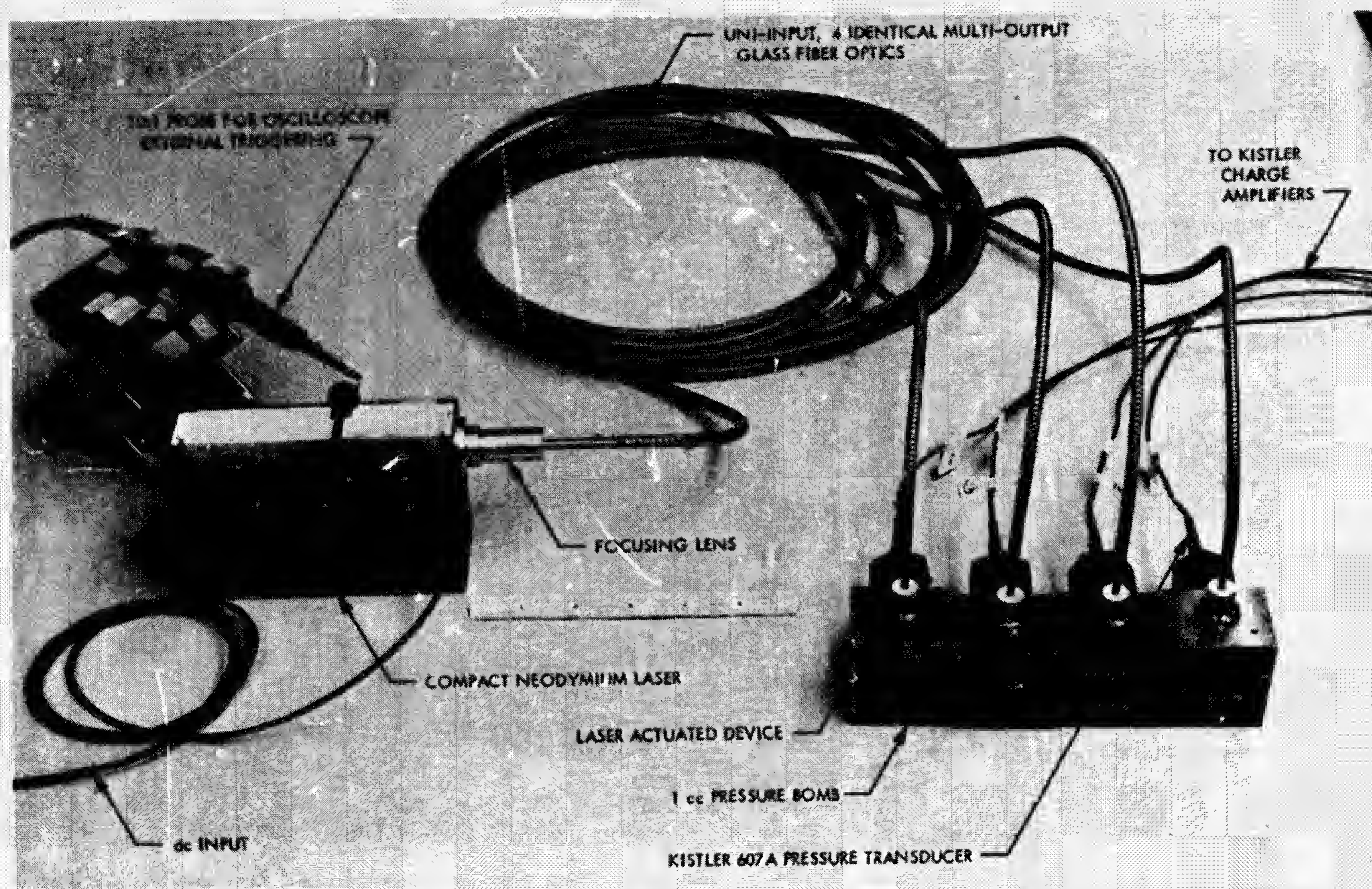
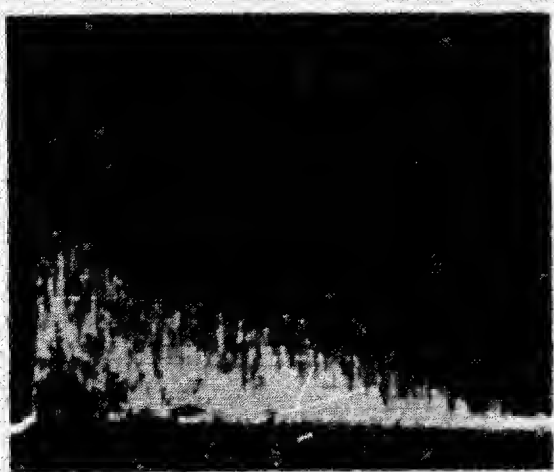
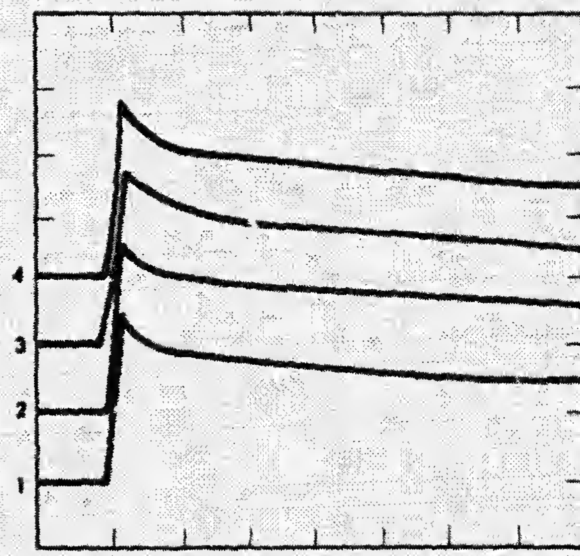


Figure 3.- The test set-ups of simultaneous initiation of multi-devices by a neodymium laser.



LASER OUTPUT
HORIZONTAL SCALE: 0.2 msec/DIVISION
VERTICAL SCALE: RELATIVE UNITS



PRESSURE OUTPUT
VERTICAL SCALE: 1.72×10^7 N/m^2/UNIT (2500 psi/UNIT)
HORIZONTAL SCALE: 0.2 msec/UNIT

LASER ENERGY: 2.8 J

LENGTH OF THE FIBER OPTICS: 3.0 m (10 ft)

FOCUSING LENS: 15 mm FOCAL LENGTH
12 mm DIAMETER

FIBER-OPTICS CONFIGURATION: UNIT-INPUT 4-IDENTICAL OUTPUTS

ZERO TIME: TRIGGERING PULSE TO FLASH LAMP

EXPLOSIVE DEVICE: JPL AP-Zr LASER SQUIB

VOLUME OF PRESSURE BOMB: 1 cc

Figure 4. Test record of simultaneous initiation of pyrotechnic devices by laser energy.